

Υ -meson pair production at LHC

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Theoretical predictions for $pp \rightarrow 2\Upsilon + X$ cross section at $\sqrt{s} = 8$ TeV for the LHCb and ATLAS kinematical conditions are obtained. A possibility to observe the new hypothetical particles containing two valence b -quarks and two valence \bar{b} -quarks is discussed.

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I. INTRODUCTION

In the recent report of the LHCb collaboration [1] a measurement of the J/ψ pair production at pp collision energy of 8 TeV was presented. The experimental cross section value of 5.1 ± 1.1 nb appeared to be close to the predicted one in the article [2], in which the leading order (LO) QCD calculations in the color singlet (CS) scheme was performed. This calculations take into account only the single parton scattering reactions (SPS). However, the double parton scattering (DPS) can also contribute to the J/ψ pair production at LHC due to the large gluon luminosity. The cross section value of double J/ψ production was roughly estimated within DPS mechanism is close to the SPS prediction.

The calculation for the process $gg \rightarrow J/\psi J/\psi$ within LO QCD + CS + SPS is a well defined procedure and give a reliable results. The calculation uncertainties are determined by a choice of scales, parton density functions, and a mass of heavy quark. The cross section value within this approach can be estimated as 4 ± 2 nb [2]. Of cause there some open questions in this calculation: the contribution from the NLO diagrams, the influence of the relative quark motion in the hard part of the matrix element, and the accounting of transverse momenta of initial gluons.

Recently the estimation of some high order contributions to the J/ψ pair production has

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been done in [3]. The effects due to the transverse momenta of initial gluons was studied in [4] within the k_T -factorization approach. Also it has been shown that the quark internal motion could influence the cross section distribution shape [2], as well as the cross section value [5]. However, all these problems need further investigation.

It is worth to note, that the standard mechanism (pQCD + CS + SPS) does not describe well enough the invariant mass distribution of J/ψ pair production [1], however it is shown that the quark motion in quarkonia could improve the agreement [6]. The p_T and y distributions for the double J/ψ production were not reported yet [1].

In the case of double Υ production quarks in quarkonia have a smaller velocity [7], thus the uncertainties caused by the quark internal motion are smaller than for the case of double J/ψ production. Therefore the formula for the cross section of the process $gg \rightarrow (Q\bar{Q}) + (Q\bar{Q})$ obtained within leading order of pQCD [8] should describe the data on the double Υ production more precisely than the data on the double J/ψ production.

What concerns a possible DPS contribution, only simplified models can be recently used to estimate its contribution due to the absence of the two-particle distribution functions for partons in a proton. This leads to the unknown uncertainties in the cross section value. Using the LHCb experimental cross section value for the inclusive single J/ψ production [9] and the conventional value for the effective DPS cross section, the cross section value of J/ψ pair production in the LHCb acceptance [10, 11] can be estimated as 4 nb. As it was noted, this value is close to the result of calculation in the SPS approach.

Later the associated production of J/ψ and open charm and the double open charm production was measured in the same experiment [12]. It appeared that the standard mechanism (pQCD + SPS) underestimates the experimental data in this channels by a factor of $3 \div 10$. The needed cross section values can be obtained within the DPS approach, which implies an independent production of two $c\bar{c}$ -pairs. However it is worth to mention, that the DPS approach can not describe kinematical distribution shapes for the both these cases.

In this paper we show that for the double Υ production in the LHCb conditions the DPS contribution is negligibly small, and therefore the double Υ production can be a better test for the perturbative QCD than double J/ψ production.

It worth to mention that the hadronic J/ψ pair production can be researched at low energies in fixed target experiments, where quark-antiquark interactions mostly contribute to

this process [13, 14]¹, as well as at high energies of LHC collider, where the gluon interaction is dominant.

Contrary to this, the double Υ production can be researched only at the LHC due to the small cross section value (which is approximately 10^3 times smaller than for the J/ψ pair production), as well as the large invariant mass needed to produce an Υ pair. It could be expected, that the gluon fusion gives the main contribution into the process at the LHC.

In this work we are mainly interested in the low invariant mass region as it is most accessible in the LHCb experiment, which specializes in heavy quarks studies. We assume, that the next leading order corrections are small for the LHCb experiment conditions. It should be noted here that at large invariant masses the high order corrections change the cross section behaviour and it becomes a constant, as well for the double J/ψ -production [16], while within the LO of perturbative QCD the cross section for these processes decreases with gluonic energy as $\sim 1/s^2$, as it is shown in [8].

ATLAS is another LHC experiment, where the Υ pair production can be researched. Despite the p_T cuts applied for muons from Υ decays, ATLAS can reconstruct Υ -mesons without cuts on their p_T [17] due to the large energy release in the leptonic Υ decay. The efficiency and the total number of reconstructed events in the low- p_T region is not expected to exceed the LHCb values, however the cross section of double Υ production in the ATLAS experiment is predicted to be larger than in LHCb.

It is worth to note that in the leading order of α_s the quarkonia pair production obeys selection rules, which are similar to those for quarkonia decays. Selection rules in the charmonia decays are confirmed by measurements of J/ψ and χ_c meson widths. In the production case two initial gluons in a color-singlet state are C-even. This is why the production of Υ -, η_b - or χ_b -meson pairs is allowed, while the combined production of two particles having a different C-parity (such as $\Upsilon + \eta_b$ and $\Upsilon + \chi_b$) is prohibited.

These selection rules put restrictions on the feed-down from the higher states. For instance the feed-down from the $\Upsilon + \chi_b$ production is expected to be less than from the $\chi_b + \chi_b$ one, because the production of the former final state is forbidden in the leading order of pQCD. Meanwhile the feed-down from the $\Upsilon + \Upsilon'$ channel can be quite large.

¹ the simultaneous production of two J/ψ -mesons was first observed in 1982 by the NA3 collaboration in the multi-muon events in pion-platinum interactions at 150 and 280 GeV and later at 400 GeV in proton-platinum collisions. These data is fairly described within the CS model [15].

We expect that the color-octet mechanism negligibly contributes to the double Υ production. Indeed, the color-octet contribution to the Υ production should be essentially smaller than the color-octet contribution to the J/ψ production, because the color-octet matrix element is suppressed by the second power of relative velocity of the quarks inside the meson. But even for the doubly J/ψ production at LHCb the color-octet should not be taken into account².

The Υ -meson pair production will be investigated in the decay mode $\Upsilon \rightarrow \mu^+\mu^-$ for the both quarkonia: $2\Upsilon \rightarrow \mu^+\mu^-\mu^+\mu^-$. The region of invariant masses of four muons near the threshold of the Υ -pair production can be interesting due to the opportunity for two diquarks $[bb]_{\bar{3}} + [\bar{b}\bar{b}]_3$ to form a bound state — a tetraquark, which could decay to $\Upsilon + \mu^+\mu^- \rightarrow \mu^+\mu^-\mu^+\mu^-$. An attraction between $\bar{3}$ and 3 color states does not exclude such a possibility, especially since similar exotic states like the $Y(3940)$ resonance, decaying to $J/\psi\omega$ [20], and the $X(4140)$ resonance, decaying to $J/\psi\phi$ [21, 22], have recently been observed. It should be mentioned that according to the LHCb experimental data, there is no evidence of the $4c$ -tetraquark, decaying into two J/ψ mesons. However $[bb]_{\bar{3}}$ is essentially smaller than $[cc]_{\bar{3}}$ and therefore the model of two attracting doubly heavy diquark can be more applicable for the $4b$ -tetraquark.

The second section of our article is devoted to the non-resonant production of Υ -meson pairs in the gluon-gluon interaction. In the third section the cross section of this process at the LHC energy of 8 TeV is calculated taking different experimental restrictions into account. The fourth section the production of $4b$ -tetraquark at the LHCb experiment is discussed.

II. DOUBLE Υ PRODUCTION

The standard method to describe the double Υ production is based on following assumptions:

1. the LO QCD can be used to calculate a matrix element of four heavy quark production;
2. b and \bar{b} quarks in Υ are in a color singlet state;

² As it is shown in [18, 19] the octet contribution becomes significant only at transverse momentum $p_T \gtrsim 15$ GeV, which corresponds to a big invariant mass of the J/ψ pair.

3. the internal motion of quark in the meson do not essentially influence the cross section value and the distribution shapes (δ -approximation);
4. the both Υ mesons are produced in a single gluon-gluon interaction (a single parton scattering, SPS).

In the leading order of perturbative QCD there are 31 Feynman diagrams describing a color-singlet Υ pairs production in the gluonic interaction.

We do not consider the contribution of quark-antiquark interaction, which is negligibly small at LHC energies.

The hadronization of $b\bar{b}$ -pair into the final Υ -meson within the δ -approximation is accounted for by the wave function of this particle at origin:

$$\begin{aligned}\psi_{\Upsilon(1S)}(r)|_{r=0} &= 0.635 \text{ GeV}^{3/2}, \\ \psi_{\Upsilon(2S)}(r)|_{r=0} &= 0.455 \text{ GeV}^{3/2}, \\ \psi_{\Upsilon(3S)}(r)|_{r=0} &= 0.400 \text{ GeV}^{3/2}.\end{aligned}\tag{1}$$

These are only nonperturbative parameters in the matrix element of $gg \rightarrow 2\Upsilon$ process. The values (1) are extracted from the leptonic widths of Υ -mesons, neglecting QCD corrections, as we do not take these corrections into account in our matrix element.

As every α_s^4 calculation, our calculation of Υ pair production is affected by the scale uncertainty. This one is of the same order of magnitude, as the b -quark mass uncertainty. Unlike the scale choice, the choice of the b -quark mass also affects on a relative yield of different bottomonia pairs.

The conventional b mass value in the matrix element equals a half mass of produced bottomonium. Alternatively, one can choose one and the same m_b value for all bottomonia pairs. We present the results obtained for the both these cases. For the second one we use $m_b = 4.73 \text{ GeV}$ in the matrix element while the mass of the particular Υ -meson is taken in the phase space.

To estimate the feed-down from higher excitations we use the PDG [23] branching fractions for $\Upsilon(2S) \rightarrow \Upsilon(1S) + X$ and $\Upsilon(3S) \rightarrow \Upsilon(1S, 2S) + X$ decays. The impact of feed-down on the cross section values is less than the uncertainties owing to the scale and the m_b choices. Nevertheless, it should be taken into account, because it effects on the relative yields of different bottomonia pairs. The $\Upsilon(1S)\Upsilon(1S)$ pair production is most influenced by feed-down,

Mode	$m_b = m_\Upsilon/2$		$m_b = 4.73 \text{ GeV}$	
	without feed-down	with feed-down	without feed-down	with feed-down
$\Upsilon(1S)\Upsilon(1S)$	36 pb	45 pb	36 pb	48 pb
$\Upsilon(2S)\Upsilon(2S)$	5.3 pb	6.0 pb	8.6 pb	9.8 pb
$\Upsilon(3S)\Upsilon(3S)$	2.3 pb	2.3 pb	4.9 pb	4.8 pb
$\Upsilon(1S)\Upsilon(2S)$	27 pb	33 pb	35 pb	44 pb
$\Upsilon(1S)\Upsilon(3S)$	18 pb	20 pb	27 pb	31 pb
$\Upsilon(2S)\Upsilon(3S)$	7.0 pb	7.4 pb	13 pb	14 pb

TABLE I: The double bottomonium production cross sections in 8 TeV pp -collisions. No kinematical cuts are imposed. A relative uncertainty of 1.4 due to the scale choice is assumed.

where it leads to the 30% increase of the yield.

The transverse momenta of the initial gluons are taken into account within the Pythia machinery.

In Tab. I we present the double bottomonium production cross sections (without kinematical cuts) estimated for the different parameters values. All these predictions were done for the 8 TeV pp collisions using the CTEQ6LL $p.d.f.$ set [24] at the scale equal to an averaged transverse mass of quarkonia. The α_s in the matrix elements of hard subprocess is also taken at this scale.

The corresponding cross section distributions on the invariant mass are shown in Fig. 1. The distribution shapes do not depend essentially on the hard scale choice, while the cross section value changes by factor of approximately 1.4 with the variation of scale by a factor of 2.

Despite the difference in masses and in feed-down contributions, shapes of distributions over the transverse momenta and rapidity of different Υ mesons do not differ significantly. At least the uncertainties caused by ambiguity in scale selection are larger. This is why, in what follows, we discuss kinematic properties of $\Upsilon(1S)$ pair production only.

Here we consider the Υ pair production at LHCb and ATLAS experiments.

The LHCb experiment, being designed for the b -physics studies, allows to measure the Υ pair production without p_T cutoff. Contrary to this, as a rule, the ATLAS experiment allows to study only relatively large p_T . However, namely the Υ production is an exclusion. Contrary to the J/ψ meson leptonic decay, the energy release in the Υ decay is large. This allows ATLAS to measure Υ mesons even at low p_T . The production cross section in ATLAS

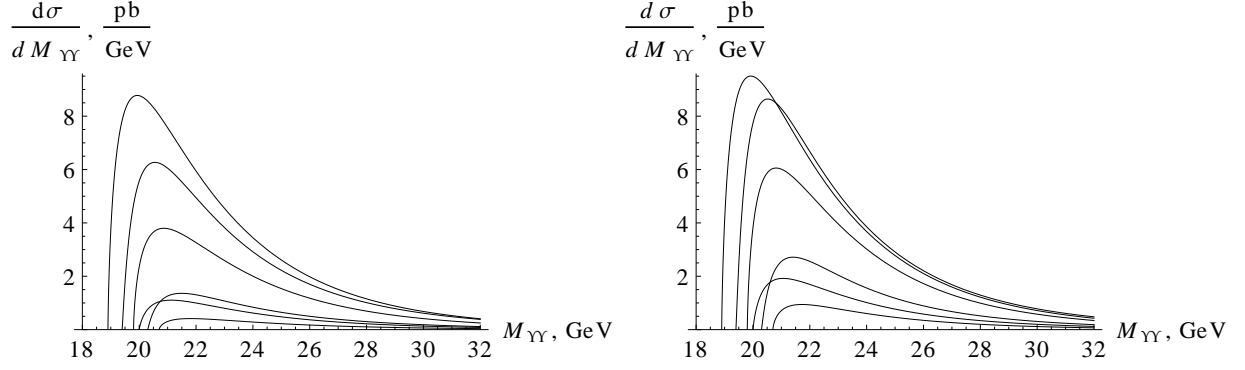


FIG. 1: The distributions over the invariant mass of Υ -meson pairs. A half of the meson mass is used for the m_b in the left plot and fixed value of $m_b = 4.73$ GeV is used in the right. From left to right curves correspond to the $\Upsilon(1S)\Upsilon(1S)$, $\Upsilon(1S)\Upsilon(2S)$, $\Upsilon(1S)\Upsilon(3S)$, $\Upsilon(2S)\Upsilon(2S)$, $\Upsilon(2S)\Upsilon(3S)$ and $\Upsilon(3S)\Upsilon(3S)$ production.

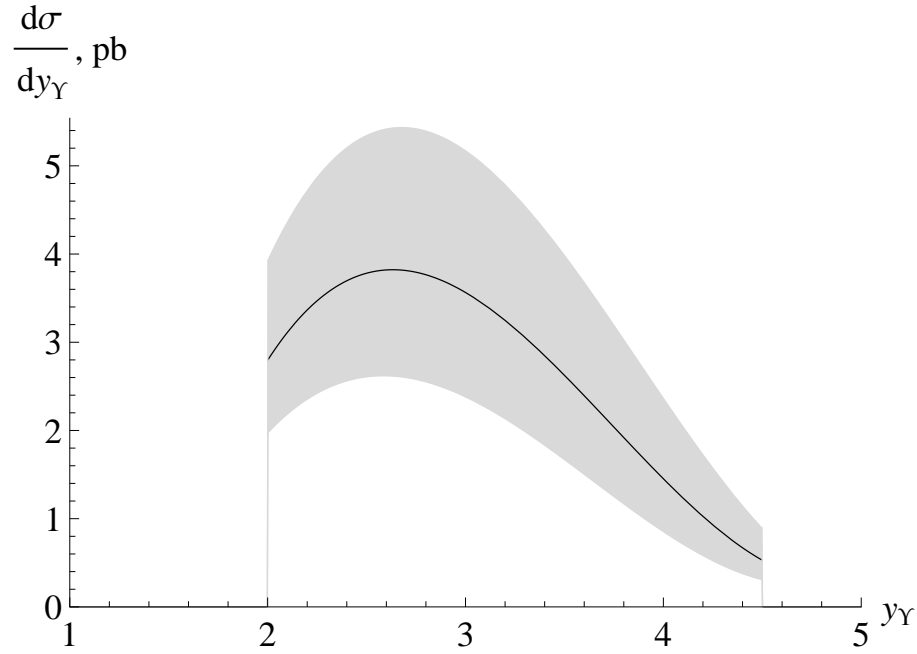


FIG. 2: The rapidity distribution of the Υ -pair in the Υ -pair production process with the LHCb rapidity cut.

conditions appears to be even larger than in the LHCb due to the wider rapidity window ($-2.5 < y < 2.5$ instead of $2 < y < 4.5$ for LHCb).

Within the SPS approach we predict the hump in the rapidity distribution of single Υ meson in the double Υ production at LHCb, as well as the hump in the rapidity distribution of single J/ψ meson in the double J/ψ production. This hump is caused by the LHCb cutoff on rapidity, which leads to the strong rapidity correlation (see Fig. 2).

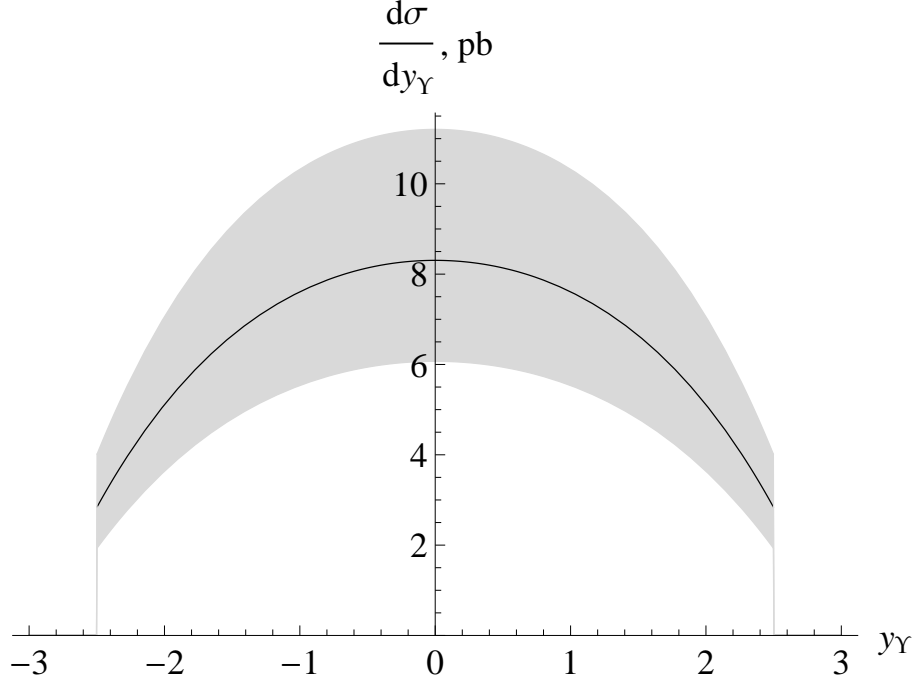


FIG. 3: Distribution over the rapidity of single Υ in the Υ -pair production process at ATLAS.

Mode	ATLAS		LHCb	
	$m_b = m_\Upsilon/2$	$m_b = 4.73 \text{ GeV}$	$m_b = m_\Upsilon/2$	$m_b = 4.73 \text{ GeV}$
$\Upsilon(1S)\Upsilon(1S)$	31 pb	33 pb	6.2 pb	6.6 pb
$\Upsilon(2S)\Upsilon(2S)$	4.2 pb	6.8 pb	0.8 pb	1.3 pb
$\Upsilon(3S)\Upsilon(3S)$	1.6 pb	3.4 pb	0.3 pb	0.6 pb
$\Upsilon(1S)\Upsilon(2S)$	23 pb	30 pb	4.5 pb	6.0 pb
$\Upsilon(1S)\Upsilon(3S)$	14 pb	21 pb	2.8 pb	4.2 pb
$\Upsilon(2S)\Upsilon(3S)$	5.2 pb	9.6 pb	1.0 pb	1.9 pb

TABLE II: The cross sections of doubly bottomonium production in 8 TeV pp -collisions. ATLAS and LHCb kinematical cuts are imposed.

The rapidity distribution in ATLAS conditions is presented in Fig. 3.

Despite the essential difference in the kinematical conditions at these facilities the distributions over the p_T of single Υ in the pair production and over the p_T of Υ pair have practically the same shapes. This why we perform here these distributions without rapidity cuts (see Fig. 4 and Fig. 5). As one can see, the different choices of hard scale value significantly affect the slope of both distributions in the high p_T area.

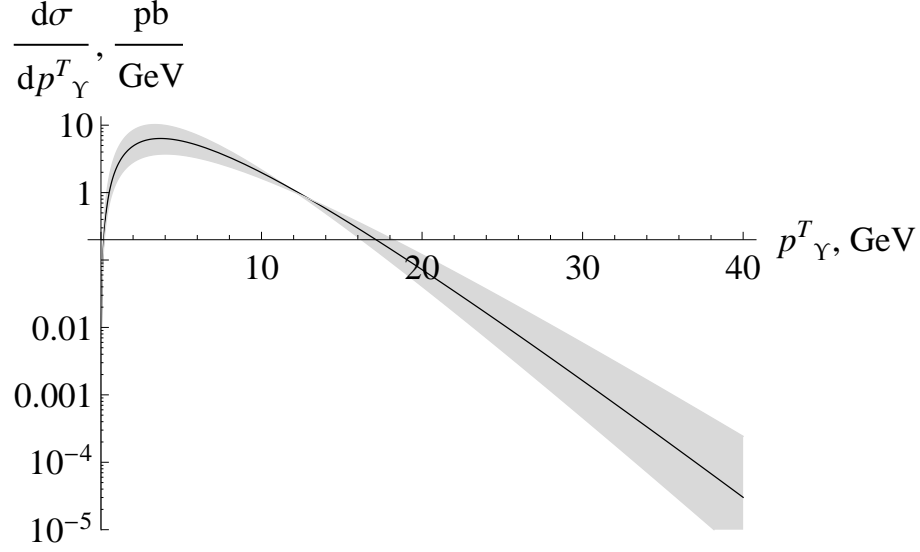


FIG. 4: The p_T distributions of the single Υ in the $\Upsilon(1S)\Upsilon(1S)$ production process at LHC depending on the scale choice.

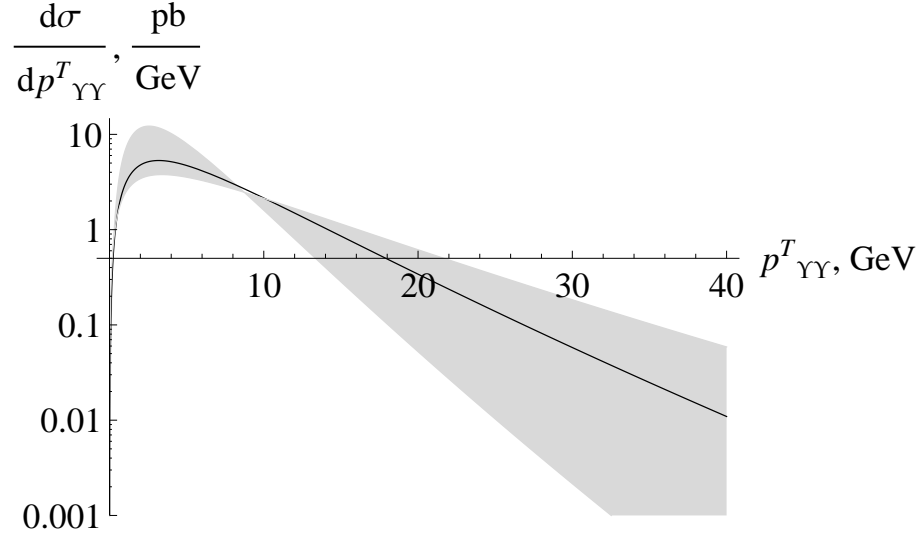


FIG. 5: Distribution over the p_T of the Υ -pair in the $\Upsilon(1S)\Upsilon(1S)$ production process at LHC depending on the scale choice.

In the LHC conditions a huge density of low- x gluons leads to the increase of multiple gluon-gluon interactions probability within a single proton-proton collision. In the DPS approach, which implies a particles production in two independent subprocesses, the cross section is written down as follows:

$$\sigma_{\text{DPS}}^{AB} = \frac{m}{2} \frac{\sigma_{\text{SPS}}^A \sigma_{\text{SPS}}^B}{\sigma_{\text{eff}}}. \quad (2)$$

where the parameter $\sigma_{\text{eff}} = 14.5 \text{ mb}$ was measured in the four jets and three jets plus photon modes by the CDF and D0 detectors [10, 11], and the parameter m equals 1 for identical subprocesses and 2 for different ones. As it was shown in [25–27], the DPS mechanism could play an essential role in the double J/ψ production, because the predictions for the double J/ψ production within SPS and DPS have the same order of magnitude. For the double Υ production the DPS mechanism contributes only about 10% of the SPS cross section and, therefore, can be neglected (see [27]).

III. THE POSSIBILITY OF OBSERVATION OF THE $4b$ -TETRAQUARK AT LHCb

Within QCD two heavy quarks in the $\bar{3}$ color state attracts each other, forming the $[QQ]_{\bar{3}}$ diquark. An attraction between $\bar{3}$ and 3 color states does not exclude a possibility to observe the heavy tetraquark $[QQ]_{\bar{3}}[\bar{Q}\bar{Q}]_3$. The spectroscopy of such systems can be easily investigated under assumption that these diquarks are almost point-like [28]. Within this approach it was predicted that all $4b$ -tetraquark states have masses below the $\Upsilon + \Upsilon$ threshold. Therefore such states can not contribute to the double Υ production. Nevertheless the $4b$ tetraquark could be searched in the decay mode $[bb]_{\bar{3}}[\bar{b}\bar{b}]_3 \rightarrow \Upsilon + \Upsilon^* \rightarrow \Upsilon \mu^+ \mu^-$. According to [28] the ground state of $4b$ tetraquark splits into tree states due to the spin-spin interaction:

$$\begin{aligned} 0^{++} : \quad & M = 18.754 \text{ GeV}, \quad M - M_{\text{th}} = -544. \text{ MeV}, \\ 1^{+-} : \quad & M = 18.808 \text{ GeV}, \quad M - M_{\text{th}} = -490. \text{ MeV}, \\ 2^{++} : \quad & M = 18.916 \text{ GeV}, \quad M - M_{\text{th}} = -382. \text{ MeV}. \end{aligned}$$

It worth to note, that at the present time there are no reliable methods to estimate the cross section value of the $4b$ tetraquark production.

IV. CONCLUSIONS

The observation of J/ψ pair production has opened an interesting discussion about the contributions of SPS and DPS mechanisms into the production process. The SPS contribution is estimated in the framework of well known and well tested pQCD approach. The

second mechanism, DPS, is not well studied experimentally yet. However it allows to understand the large cross sections of the J/ψ plus open charm production and the double open charm production at LHCb. For the double J/ψ production the SPS and DPS approaches give comparable predictions, which are of the same order with the experimental results.

The situation is different for the double Υ production. The both SPS and DPS calculations for it stand on the same basis as for the double J/ψ production, but for this case the SPS prediction is about an order of magnitude larger than the DPS one. Thus, the study of Υ pair production will allow us to understand, if we describe the SPS production of quarkonia correctly.

The observation of double J/ψ -meson production [1] was reported by LHCb soon after the measurement of inclusive J/ψ production [9]. The measurement of Υ -meson inclusive production have been recently reported in [29]. It is based on the 25 pb^{-1} integrated luminosity collected in 2010. The integrated luminosity collected both in 2011 and in 2012 exceeds 1 fb^{-1} . This corresponds to more than 40 times larger statistics. Taking into account the estimated here cross section value and the leptonic branching of Υ -meson (2.5%) one can expect several dozens of events with two Υ mesons in both 2011 and 2012 data.

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- [1] R. Aaij et al. (LHCb), Phys. Lett. **B707**, 52 (2012), 1109.0963.
 - [2] A. V. Berezhnoy, A. K. Likhoded, A. V. Luchinsky, and A. A. Novoselov, Phys. Rev. **D84**, 094023 (2011), 1101.5881.
 - [3] S. Baranov, A. Snigirev, N. Zotov, A. Szczurek, and W. Schafer (2012), 1210.1806.
 - [4] S. Baranov, Phys.Rev. **D84**, 054012 (2011).
 - [5] A. Martynenko and A. Trunin (2012), 1207.3245.
 - [6] A. Berezhnoy, A. Likhoded, A. Luchinsky, and A. Novoselov (2012), 1204.1058.
 - [7] G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys.Rev. **D51**, 1125 (1995), hep-ph/9407339.
 - [8] B. Humpert and P. Mery, Z. Phys. **C20**, 83 (1983).
 - [9] R. Aaij et al. (LHCb), Eur. Phys. J. **C71**, 1645 (2011), 1103.0423.

- [10] F. Abe et al. (CDF), Phys. Rev. **D56**, 3811 (1997).
- [11] V. M. Abazov et al. (D0), Phys. Rev. **D81**, 052012 (2010), 0912.5104.
- [12] LHCb Collaboration (2012), LHCb-PAPER-2012-003.
- [13] J. Badier et al. (NA3 Collaboration), Phys.Lett. **B114**, 457 (1982).
- [14] J. Badier et al. (NA3 Collaboration), Phys.Lett. **B158**, 85 (1985).
- [15] V. G. Kartvelishvili and S. M. Esakiya, Yad. Fiz. **38**, 722 (1983).
- [16] V. Kiselev, A. Likhoded, S. Slabospitsky, and A. Tkabladze, Sov.J.Nucl.Phys. **49**, 682 (1989).
- [17] G. Aad et al. (ATLAS Collaboration), Phys.Lett. **B705**, 9 (2011), 1106.5325.
- [18] C.-F. Qiao, L.-P. Sun, and P. Sun, J.Phys.G **G37**, 075019 (2010), 0903.0954.
- [19] P. Ko, C. Yu, and J. Lee, JHEP **01**, 070 (2011), 1007.3095.
- [20] N. Drenska, R. Faccini, F. Piccinini, A. Polosa, F. Renga, et al., Riv.Nuovo Cim. **033**, 633 (2010), 1006.2741.
- [21] F. Wick (CDF Collaboration), PoS **EPS-HEP2009**, 085 (2009), 1011.0616.
- [22] X. Liu, Z.-G. Luo, and S.-L. Zhu, Phys.Lett. **B699**, 341 (2011), 1011.1045.
- [23] J. Beringer et al. (Particle Data Group), Phys.Rev. **D86**, 010001 (2012).
- [24] J. Pumplin et al., JHEP **07**, 012 (2002), hep-ph/0201195.
- [25] C. H. Kom, A. Kulesza, and W. J. Stirling, Phys. Rev. Lett. **107**, 082002 (2011), 1105.4186.
- [26] S. Baranov, A. Snigirev, and N. Zotov, Phys.Lett. **B705**, 116 (2011), 1105.6276.
- [27] A. Novoselov (2011), 1106.2184.
- [28] A. Berezhnoy, A. Luchinsky, and A. Novoselov (2011), 1111.1867.
- [29] R. Aaij et al. (LHCb Collaboration), Eur.Phys.J. **C72**, 2025 (2012), 1202.6579.